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SCIENCE DIRECT

Progress in Aerospace Sciences 41 (2005) 471–513

PROGRESS IN AEROSPACE SCIENCES

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Scramjets and shock tunnels—The Queensland experience

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Abstract

This article reports on the use of a shock tunnel to study the operation of scramjet powered configurations at sub-orbital velocities above 2 km/s. Thrust, as given by a net thrust equation, is used as a figure of merit throughout the study. After a short description of the shock tunnel used and its operating characteristics, experiments on the combustion release of heat in a constant area duct with hydrogen fuel are reviewed. The interaction between heat release in the combustion wake and the walls of the duct produced pressure distributions which followed a binary scaling law, and indicated that the theoretically expected heat release could be realized in practice, albeit with high pressure or long combustion ducts. This heat release, combined with attainable thrust nozzle characteristics and a modest level of configuration drag, indicated that positive thrust levels could be obtained well into the sub-orbital range of velocities. Development of a stress wave force balance for use in shock tunnels allowed the net thrust generated to be measured for integrated scramjet configurations and, although the combination of model size and shock tunnel operating pressure prevented complete combustion of hydrogen, the cruise condition of zero net thrust was achieved at 2.5 km/s with one configuration, while net thrust was produced with another configuration using an ignition promoter in hydrogen fuel. Nevertheless, the combination of boundary layer separation induced inlet choking and limited operating pressure levels prevented realization of the thrust potential of the fuel. This problem may be alleviated by recent increases in the shock tunnel operating pressures, and by promising research involving inlet injection of the fuel.

Research on the drag component of the net thrust equation resulted from the development of a fast response skin friction gauge. It was found that existing theories of turbulent boundary skin friction predicted the skin friction when combustion of hydrogen occurred outside the boundary layer, but combustion within the boundary layer dramatically reduced the skin friction. Finally, for the first time in the world, supersonic combustion was produced in a free flight experiment. This experiment validated shock tunnel results at stagnation enthalpies near 3 MJ/kg.

Contents

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0376-0421/$ - see front matter
doi:10.1016/j.paerosci.2005.08.002

Nomenclature

A	flow cross-sectional area (m^2)
A_∞	frontal area (m^2)
C_D	drag coefficient $= 2D/(\rho_\infty U^2 A_\infty)$
C_{TN}	thrust coefficient $= 2T_N/(\rho_\infty U^2 A_\infty)$
C_j	injected fuel thrust coefficient
D	drag (N)
e_n	nozzle efficiency = thrust/(one-dim. nozzle thrust)
F	thrust function
g	gravitational acceleration (m/s^2)
I_{sp}	specific impulse (s)
M	Mach number
M_c	Mach number after combustion heat release
n	$\Delta T/T_{NN}$ combustion duct + thrust nozzle efficiency
p	pressure (Pa)
P_c	pressure after combustion heat release (Pa)
ΔQ	heat released by fuel combustion in air (= 3.45 MJ/kg for stoichiometric hydrogen)
T_N	net forward thrust (N)
T_{NN}	net forward thrust when all of combustion heat release is converted to stream kinetic energy (N)
ΔT	thrust increment with one-dimensional nozzle (N)
U	freestream velocity (m/s)
γ	ratio of specific heats
θ	flow direction
θ_D	initial nozzle divergence angle
v	Prandtl–Meyer function
ρ	density (kg/m^3)
ρ_∞	freestream density (kg/m^3)